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FATIGUE FRACTURE AND STRAIN HARDENING OF HIGH CARBON
HARDENED ALLOY STEEL (U) COLORADO SCHOOL OF MINES GOLDEN
G KRAUSS 84 JUN 87 ARO-21316 4-MS DAAG29-84-K-8127

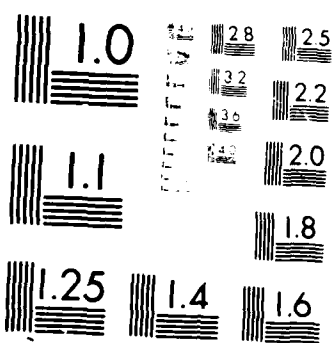
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FATIGUE, FRACTURE AND STRAIN HARDENING OF HIGH CARBON
HARDENED ALLOY STEEL

ARO 21316.4-MS

FINAL REPORT

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GEORGE KRAUSS

JUNE 4, 1987

U.S. ARMY RESEARCH OFFICE

CONTRACT/GRANT NUMBER

DAAG29-84-K-0127

COLORADO SCHOOL OF MINES
GOLDEN, COLORADO 80401

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ABSTRACT

Medium and high carbon alloy steels have been heat treated to microstructures of low-temperature tempered martensite and retained austenite. Four point bending fatigue testing of 0.8 pct C steels showed that low cycle fatigue resistance was directly related to retained austenite content. The strain-induced transformation of retained austenite substantially increased strain hardening rates of the composite tempered martensite-austenite microstructures at high strains and increased the number of cycles required to initiate fatigue cracks at prior austenite grain boundaries in specimens with the highest retained austenite content. Transmission electron microscopy identified the transition carbides formed on tempering as the orthorhombic eta carbide, and the increasing density of the transition carbides with increases in carbon content was the major carbon-dependent structural parameter which correlated with flow stresses and strain hardening rates in medium carbon tempered martensite. Elastic limits, as measured with strain gages mounted in compression specimens, decreased with increasing retained austenite content. In medium carbon steels with lath martensite morphologies the retained austenite transformed to martensite by stress induced mechanisms, and in high carbon steels with plate martensite morphologies, the retained austenite transformed by strain-induced mechanisms.

STEAM CONDENSERS

CONDIMENTS

UF PEPPER
SEASONINGS
SPICES
BT FOOD

CONDITIONED RESPONSE

BT *RESPONSE(BIOLOGY)

CONDITIONING(LEARNING)

BT *LEARNING

CONDUCTION BANDS

BT ENERGY BANDS

CONDUCTION(HEAT TRANSFER)

BT HEAT TRANSFER

CONDUCTIVE LIQUIDS

BT *LIQUIDS

CONDUCTIVITY

BT PHYSICAL PROPERTIES
NT *ELECTRICAL CONDUCTIVITY
THERMAL CONDUCTIVITY

CONDUIT PLIERS

BT *PLIERS

CONDUITS

CONFERENCING(COMMUNICATIONS)

BT COMMUNICATION AND RADIO
SYSTEMS

CONFIDENCE LEVEL

CONFIDENCE LIMITS

BT *STATISTICAL ANALYSIS

CONFIGURATION MANAGEMENT

BT MANAGEMENT

CONFIGURATIONS

NT *AERODYNAMIC CONFIGURATIONS
ANTENNA CONFIGURATIONS
COAXIAL CONFIGURATIONS
CRUCIFORM CONFIGURATIONS
*SHAPE
STUE CONFIGURATION

CONFINED ENVIRONMENTS

Restricted or isolated
environments involving any
number of people, such as in
spacecraft, submarines, or bomb
shelters.

BT ENVIRONMENTS

CONFINEMENT(GENERAL)

NT CONFINEMENT(NUCLEAR REACTORS)

CONFINEMENT(NUCLEAR REACTORS)

Systems or equipment that
provide total isolation of
hazardous materials in case of
reactor accidents.

BT CONFINEMENT(GENERAL)
NUCLEAR REACTORS

CONFINEMENT(PSYCHOLOGY)

BT *STRESS(PSYCHOLOGY)

CONFLICT

CONFLUENCE

CONFORMAL MAPPING

BT *COMPLEX VARIABLES
MAPPING

CONFORMAL STRUCTURES

BT STRUCTURES

CONFORMITY

CONFRONTATION

CONGENITAL ABNORMALITIES

BT ABNORMALITIES

CONGESTION

CONGO RIVER

BT *RIVERS

CONGRESS

(81/09) - Legislature of the
United States consisting of
the Senate and the House of
Representatives
BT *UNITED STATES GOVERNMENT
NT HOUSE OF REPRESENTATIVES
SENATE

CONICAL ANTENNAS

BT *BROADBAND ANTENNAS
NT BICONICAL ANTENNAS
DISCONE ANTENNAS

CONICAL BODIES

BT BODIES
GEOMETRIC FORMS
NT FRUSTUMS

CONICAL NOZZLES

BT NOZZLES

CONICAL SCANNING

BT SCANNING

CONICAL WINGS

BT *DELTA WINGS

CONJUGATED PROTEINS

use PROTEINS(CONJUGATED)

CONJUNCTIVITIS

BT *EYE DISEASES

CONNECTICUT

BT *NEW ENGLAND

CONNECTICUT RIVER

BT *RIVERS

CONNECTING RODS

CONNECTIVE TISSUE

BT TISSUES(BIOLOGY)
NT ADIPOSE TISSUE
*BONES
CARTILAGE
FASCIA
MAST CELLS

CONNECTORS

NT *ELECTRIC CONNECTORS

CONSCIOUSNESS

CONSERVATION

NT SOIL CONSERVATION
WATER CONSERVATION
WATER RECLAMATION

CONSERVATION LAWS(MATHEMATICS)

use DIFFERENTIAL GEOMETRY

CONSISTENCY

CONSISTENCY PROOF

use CALCULUS OF VARIATIONS
and MATHEMATICAL LOGIC

CONSOLES

BT *CONTROL PANELS
NT KEYBOARDS

CONSORTIUMS

CONSTANT SPEED DRIVES

use DRIVES
and SPEED REGULATORS

CONSTANTS

NT GRUNEISEN CONSTANT

CONSTELLATIONS

CONSTRICTIONS

NT VASOCONSTRICTING

CONSTRUCTION

NT *CONSTRUCTION MATERIALS
FILAMENT WOUND CONSTRUCTION
*MODULAR CONSTRUCTION
TAPE WOUND CONSTRUCTION
UNDERWATER CONSTRUCTION

CONSTRUCTION EQUIPMENT

NT ROAD BUILDING EQUIPMENT

CONSTRUCTION MATERIALS

BT CONSTRUCTION
MATERIALS
NT *CONCRETE
MORTARS(MATERIAL)

CONSUMABLE ELECTRODE PROCESS

BT *ARC MELTING

CONSUMER PROBLEMS

BT CONSUMERS

CONSUMERS

NT CONSUMER PROBLEMS

CONSUMPTION

NT ALCOHOL CONSUMPTION
ENERGY CONSUMPTION
FOOD CONSUMPTION
*FUEL CONSUMPTION
OIL CONSUMPTION
OXYGEN CONSUMPTION

CONTACT FUZES

use IMPACT FUZES

CONTACT LENSES

(84/12) - A thin lens fitted
over the cornea to correct
defects of vision
BT *OPTICAL LENSES

- SPEECH COMPRESSION
THERMOCOMPRESSION
TIME COMPRESSION
- COMPRESSION IGNITION**
BT *IGNITION
- COMPRESSION IGNITION ENGINES**
BT *INTERNAL COMBUSTION ENGINES
NT DIESEL ENGINES
- COMPRESSION MOLDING**
BT *MOLDING TECHNIQUES
- COMPRESSION RATIO**
BT RATIOS
- COMPRESSION SHOCK**
use SHOCK WAVES
- COMPRESSIVE PROPERTIES**
Response to compression loads.
UF COMPRESSIBILITY
COMPRESSIVE STRENGTH
BT *MECHANICAL PROPERTIES
NT BEARING STRENGTH
- COMPRESSIVE STRENGTH**
use COMPRESSIVE PROPERTIES
- COMPRESSOR BLADES**
BT *ROTOR BLADES(TURBOMACHINERY)
NT AXIAL FLOW COMPRESSOR BLADES
- COMPRESSOR COMPONENTS**
(84-12)
UF COMPRESSOR PARTS
BT COMPRESSORS
- COMPRESSOR NOISE**
BT *MACHINERY NOISE
- COMPRESSOR PARTS**
use COMPRESSOR COMPONENTS
- COMPRESSOR ROTORS**
BT ROTORS
- COMPRESSOR STATORS**
BT STATORS
- COMPRESSORS**
NT AIR COMPRESSORS
COMPRESSOR COMPONENTS
GAS COMPRESSORS
HIGH PRESSURE COMPRESSORS
MIXED FLOW COMPRESSORS
REFRIGERANT COMPRESSORS
*ROTARY COMPRESSORS
*SUPERCHARGERS
- COMPTON SCATTERING**
BT *GAMMA RAY SCATTERING
- COMPTROLLERS**
BT FINANCE
- COMPUTATIONAL LINGUISTICS**
BT LINGUISTICS
NT MACHINE TRANSLATION
- COMPUTATIONS**
BT *MATHEMATICAL ANALYSIS
- COMPUTER AIDED DESIGN**
BT COMPUTER APPLICATIONS
- COMPUTER AIDED DIAGNOSIS**
BT DIAGNOSIS(GENERAL)
- COMPUTER AIDED INSTRUCTION**
BT COMPUTER APPLICATIONS
*TEACHING METHODS
- COMPUTER AIDED MANUFACTURING**
(84/12) - The use of computers to communicate work instructions to automate machinery for the handling and processing needed to produce a workplace
- COMPUTER APPLICATIONS**
NT COMPUTER AIDED DESIGN
COMPUTER AIDED INSTRUCTION
*COMPUTERIZED SIMULATION
MEDICAL COMPUTER APPLICATIONS
- COMPUTER ARCHITECTURE**
BT *COMPUTERS
- COMPUTER COMMUNICATIONS**
BT COMMUNICATION AND RADIO SYSTEMS
- COMPUTER FILES**
BT *FILES(RECORDS)
- COMPUTER GRAPHICS**
BT DISPLAY SYSTEMS
GRAPHICS
- COMPUTER LOGIC**
BT LOGIC
- COMPUTER OPERATORS**
BT *OPERATORS(PERSONNEL)
- COMPUTER PERSONNEL**
BT PERSONNEL
NT PROGRAMMERS
- COMPUTER PRINTOUTS**
- COMPUTER PROGRAM DOCUMENTATION**
BT COMPUTER PROGRAMS
DOCUMENTS
- COMPUTER PROGRAM RELIABILITY**
- COMPUTER PROGRAM VERIFICATION**
- COMPUTER PROGRAMMING**
UF CODING(COMPUTERS)
PROGRAMMING(COMPUTERS)
BT COMPUTER PROGRAMS
NT AUTOMATIC PROGRAMMING
CONTROL SEQUENCES
DEBUGGING(COMPUTERS)
MACHINE CODING
MACROPROGRAMMING
MICROPROGRAMMING
- COMPUTER PROGRAMS**
NT COMPILERS
COMPUTER PROGRAM
DOCUMENTATION
*COMPUTER PROGRAMMING
EXECUTIVE ROUTINES
FIELDS(COMPUTER PROGRAMS)
FIRMWARE
*PROGRAMMING LANGUAGES
SUBROUTINES
- COMPUTERIZED SIMULATION**
BT COMPUTER APPLICATIONS
*MATHEMATICAL MODELS
NT ANALOG SIMULATION
DIGITAL SIMULATION
HYBRID SIMULATION
- COMPUTERIZED TOMOGRAPHY**
- COMPUTERS**
BT *DATA PROCESSING EQUIPMENT
NT ANALOG COMPUTERS
ASYNCHRONOUS COMPUTERS
*CENTRAL PROCESSING UNITS
COMPUTER ARCHITECTURE
*DIGITAL COMPUTERS
*FIRE CONTROL COMPUTERS
GUIDANCE COMPUTERS
GUIDED MISSILE COMPUTERS
HYBRID COMPUTERS
*INPUT OUTPUT DEVICES
*MEMORY DEVICES
MICROCOMPUTERS
MINICOMPUTERS
NAVIGATION COMPUTERS
SUPERCOMPUTERS
- CONCAVE BODIES**
BT BODIES
- CONCEALMENT**
- CONCENTRATED FOODS**
BT FOOD
- CONCENTRATION(CHEMISTRY)**
BT CONCENTRATION(COMPOSITION)
- CONCENTRATION(COMPOSITION)**
NT CONCENTRATION(CHEMISTRY)
DEUTERIUM ION CONCENTRATION
- CONCRETE**
BT *CONSTRUCTION MATERIALS
NT *REINFORCED CONCRETE
SHOTCRETE
- CONCUSSION**
BT WOUNDS AND INJURIES
- CONDENSATION**
Change of state from gas or vapor to liquid or solid; also meteorological phenomenon
Excludes chemical reaction
NT *ATMOSPHERIC CONDENSATION
CONDENSATION NUCLEI
- CONDENSATION NUCLEI**
BT CONDENSATION
- CONDENSATION REACTIONS**
UF REFORMATSKY REACTIONS
BT CHEMICAL REACTIONS
NT GRIGNARD REACTIONS
- CONDENSATION TRAILS**
UF CONTRAILS
EXHAUST TRAILS
VAPOR TRAILS
- CONDENSER TUBES**
BT TUBES
- CONDENSERS(LIQUEFIERS)**
NT REFRIGERANT CONDENSERS

SUMMARY OF RESULTS

A major research effort previously supported by the Army Research Office at the Colorado School of Mines had led to the identification of the microstructural features associated with the fracture surface morphologies of hardened medium and high carbon steels. The findings were based on impact and fracture toughness testing with CVN and compact tension specimens. The work related carbide structures produced during the austenitizing, quenching and tempering stages of heat treatment to various fracture morphologies and levels of toughness.

The present contract was dedicated to extending the fracture studies to fatigue of hardened steels and to evaluating the effects of tempered martensite-austenite composite microstructures on the plastic flow and strain hardening of medium and carbon steels.

Table I lists the personnel associated with the present ARO contract and Table II lists the theses and papers which have been prepared as a result of the research efforts of the personnel involved in the ARO program. The following paragraphs summarize the results of the various component investigations of the program.

TABLE I

Personnel Associated with the Research of
ARO Contract DAAG29-84-K-0127

<u>Name</u>	<u>Position</u>
J. Bruce Kelley	M.S. Candidate
Kenneth P. Hayes	M.S. Candidate
Mark A. Zaccone	M.S. Candidate
Craig Van Thyne	M.S. Candidate
Gu Baozhu	Visiting Scientist
	Beijing Aeronautical Institute
J.M.B. Losz	Postdoctoral Associate
George Krauss	Principal Investigator

Kelley (2,6) performed four-point bending fatigue studies of a series of 0.8C steels with varying amounts of chromium. The various amounts of chromium in the alloys were designed to change austenite-carbide boundaries during austenitizing, but the major effect of increasing chromium content was to lower M_s and increase the amount of retained austenite in the tempered martensite-austenite microstructures of heat treated specimens. Reheating treatments produced dispersions of retained carbide particles, similar to those studied by Brown (10) and Hayes (1), and resulted in finer martensite-austenite structures. The fatigue tests showed that improved low cycle fatigue life directly correlated with increasing amounts of retained austenite and microstructural refinement.

Zaccone (3,13) examined the plastic deformation and strain hardening of the same steels tested by Kelley in an effort to understand the role retained austenite plays in the tempered martensite-austenite composite microstructures. He examined the plastic response in both the microstrain and macrostrain regimes by compression testing. Strain gages were used to follow the microstrain deformation behavior. Three stages of deformation behavior were found. The first stage was directly dependent on the amount and morphology of the retained austenite, with the specimens with the most retained austenite having the lowest elastic limits. The second stage was independent of the amount of retained austenite, while the third stage, marked by a decrease in the rate of decrease in strain hardening rates, was again dependent on austenite content. The specimens with the highest austenite content had the highest strain hardening rates, behavior which was shown to be a result of strain-induced transformation of austenite to martensite. It is high strain hardening rates associated with microstructures with high retained austenite contents which explain the results of Kelley's fatigue testing. Instability and crack initiation at embrittled austenite grain boundaries is delayed in specimens with high retained austenite content. Examination of plastic zones at points of fatigue crack initiation confirm that substantial strain induced transformation of retained austenite is associated with fatigue crack development.

The morphology and fine structure of tempered martensites in medium and high carbon steel (5,7-0) were further characterized. In particular, the very fine transition carbide distributions, dislocation substructures, and retained austenite contents (11,12) of a series of medium carbon 41XX steels containing 0.3, 0.4, and 0.5 pct carbon were evaluated by transmission electron microscopy and related to deformation and fracture behavior. The flow stresses of tempered martensite in steels containing 10.3 to 0.5 pct carbon was linearly dependent on carbon content. Austenite grain size, martensite lath size and martensite packet size were constant. However, the density of transition carbides increased, and spacing of the carbides decreased, and retained austenite increased with increasing carbon content. Strain hardening and flow stresses in the microstrain regime were dependent on retained austenite and stress controlled transformation of the austenite to martensite. At higher strains, the substructure of the tempered martensite controlled deformation, with the higher carbon structures exhibiting higher strain hardening rates consistent with the finer spacings of the transition carbides in these structures.

The study (4) on the boron-containing carburizing steels is still in progress. The work is being done in cooperation with the ASME Gear Research Institute. Gears have been fabricated and heat treated and single teeth have been subjected to low cycle bending fatigue. The boron containing steels showed low cycle fatigue resistance intermediate to that of carburized 8627 and 4820 gear teeth. All steels failed by intergranular fatigue crack initiation, apparently in association with oxides produced during gas carburizing.

The details of the various investigations performed in the ARO program are or will be given in the theses and papers listed in Table II.

TABLE II

List of Publications Based on Research Supported by
ARO Contract DAAG29-84-K-0127
July 1984 through February 1987

THESES

1. Kenneth P. Hayes: "The Effect of Intercritical Heating and Phosphorus on Austenite Formation and Carbide Distribution of AISI 52100 Steel", M.S. Thesis No. T-2971, Colorado School of Mines, Golden, Colorado, October 1984.
2. J.B. Kelley: "The Effects of Chromium on the Microstructure and Bending Fatigue Behavior of 0.82 pct C, 1.75 pct Ni, and 0.75 pct Mo Steels", M.S. Thesis No. T-2942, Colorado School of Mines, Golden, Colorado, October 1984.
3. Mark A. Zacccone: "Flow Properties of High Carbon Tempered Martensite", M.S. Thesis No. T-3394, Colorado School of Mines, Golden, Colorado (to be defended in June 1987).
4. Craig Van Thyne: "Fracture of Carburized Boron-Containing Steel", M.S. Thesis (to be completed Fall 1987).

TECHNICAL PAPERS

5. George Krauss: "Tempering and Structural Change in Ferrous Martensitic Structures", in Phase Transformations in Ferrous Alloys, edited by A.R. Marder and J.I. Goldstein, TMS-AIME, Warrendale, Pennsylvania, 1984, pp. 101-123.
6. J.B. Kelley and G. Krauss: "The Effect of Chromium on Microstructure and Bending Fatigue of 0.75Mo-1.8Ni C Steels", Proceedings of the 4th International Congress on Heat Treatment of Materials, June 1985, Berlin, vol. 1, pp. 147-163.
7. G. Krauss: "Martensite Morphology in Steels", Proceedings of the 4th International Congress on Heat Treatment of Materials, June 1985, Berlin, vol. 1, pp. 0.1-0.14.
8. G. Krauss: "Struktur von Martensit in Stählen", Härterei-Technische Mitteilungen, 41, 1986, pp. 56-60 (translation of paper #7 into German).
9. G. Krauss: "Morphologie de la Martensite dans les Aciers", Traitement Thermique, 201, 1986, pp. 15-19 (translation of paper #7 into French).

TABLE II (continued)

10. E.L. Brown and G. Krauss: "Retained Carbide Distribution in Intercritically Austenitized 52100 Steel", Metallurgical Transactions A, Vol. 17A, 1986, pp. 31-36.
11. G. Baozhu, J.M.B. Losz, and G. Krauss: "Substructure and Flow Strength of Low Temperature Tempered Medium Carbon Martensite", in Proceedings of the International Conference on Martensitic Transformations (1986), The Japan Institute of Metals, pp. 367-374.
12. G. Baozhu and G. Krauss: "The Effect of Low-Temperature Isothermal Heat Treatments on the Fracture of 4340 Steel", J. Heat Treating, 4, 1986, pp. 365-372.
13. M.A. Zaccane, J.B. Kelley, and G. Krauss: "Fatigue and Strain Hardening of High Carbon-Martensite-Austenite Composite Microstructures", to be published in Heat Treatment '87, The Institute of Metals, London.

END

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